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ROCKET OBSERVATIONS OF SOLAR PROTONS
DURING THE NOVEMBER 1960 EVENTS, 1 [PART]

N63-85750

Code 5

[7]

K. W. Ogilvie, D. A. Bryant and L. R. Davis
NASA, Goddard Space Flight Center
Greenbelt, Maryland

Rocket Observations of Solar Protons during the November 1960 Events, 1

K. W. OGILVIE, D. A. BRYANT, AND L. R. DAVIS

Goddard Space Flight Center
National Aeronautics and Space Administration, Greenbelt, Maryland

Abstract. In this paper we describe the results of three Nike-Cajun rocket flights made during the November 12, 1960, solar proton event. By means of Geiger counter and scintillation counter measurements the spectrum of protons has been extended downward in energy to 0.2 Mev. A group of particles with energy between 0.2 and 1 Mev has been found, and it is suggested that this group may not be part of the flare-accelerated spectrum, but may be associated with the plasma in the earth-sun region. The spectrum in the low-energy region above 1 Mev cannot be represented by a simple extrapolation of the spectrum at higher energies as observed, for instance, by means of balloons.

Introduction. This paper describes observations of solar protons made during November 1960 with equipment carried clear of the atmosphere in Nike-Cajun rockets from Fort Churchill, Canada (geomagnetic coordinates 69°N, 338°). The results presented here extend the spectrum of a solar proton event to lower energies than have been observed either by satellite measurements [*Lin*, 1961] or by balloon measurements [*Winckler*, 1960; *Anderson and Enemark*, 1960] in which the particles observed must be able to penetrate a few grams per square centimeter of the atmosphere. The main features of polar-cap absorption have been explained qualitatively, assuming the incoming particles to be protons with an energy spectrum of a simple form. It is of considerable interest, therefore, to extend the directly observed energy spectrum to these lower energies where the particles are more sensitive to the magnetic properties of the earth-sun region. The present experiment was designed to give the energy spectrum of solar protons with energies between 200 kev and about 200 Mev, and to study their direction of incidence at the top of the atmosphere. In this paper, results obtained during the November 12 event are described. Results obtained with similar equipment during the September 3 event have been reported previously [*Davis, Fichtel, Guss, and Ogilvie*, 1961], but due to equipment difficulties at the time, the September 3 measurements did not cover the extended energy range of those reported here.

Apparatus. To record protons over a wide energy range, and to provide redundancy in the measurements, three different detectors were used on each flight. Figure 1 shows the location in the rocket of these detectors. An Anton 302 Geiger counter mounted parallel to the axis of the rocket was used to obtain particle intensity in the energy region 22 Mev to 70 Mev. This energy region was scanned by the Geiger counter as the motion of the rocket placed varying amounts of absorber between it and the incoming particles. The atmospheric absorption of protons observed during the ascent of the rocket was used to extend the information to higher energies. Although the acceptance angle of the Geiger counter for 22 Mev protons, the lowest-energy protons counted, was 2π steradians, it was possible to obtain some information about the angular distribution of these particles from the study of the rate as a function of rocket motion. A CsI crystal, 0.25 g/cm^2 thick, behind a 7 mg/cm^2 Al window was used for the region 2 Mev to 160 Mev, and a ZnS powder phosphor behind a 0.3 mg/cm^2 Ni window was used for the region 200 kev to 2 Mev. The axis of both the CsI and ZnS scintillation detectors made an angle of 45° to the axis of the rocket and the acceptance angle for particles entering through the windows of these detectors was 15°. The results are corrected for particles entering through the body of the rocket.

The scintillation detectors examined the energy spectrum in more detail than the Geiger counter; the counting rate of these detectors above six pulse height levels was obtained by using an
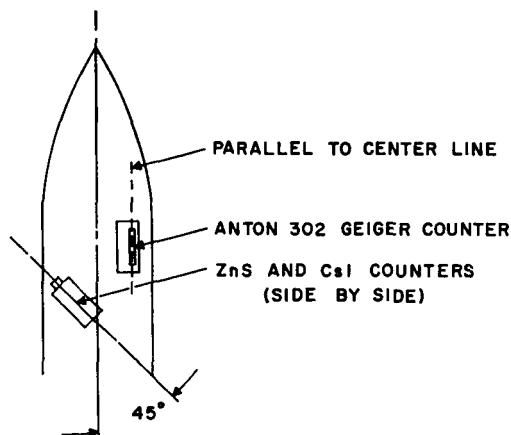
Fig. 1. Diagram showing the arrangement of detectors in the rocket.

amplifier with a fixed discrimination level and a variable resistance-capacitance anode load for the photomultiplier, changed cyclically by a motor-driven switch. In order to cover a wide range of intensity values, the pulses from all detectors were fed to rate circuits, where they were superimposed on a d-c level logarithmically related to the rate. This level was used to give the rate when the pulses were too frequent to distinguish on the telemetry record. This arrangement is shown schematically in Figure 2.

The curve in Figure 3 shows the pulse height given by the phototube when protons of various energies are incident on the crystal of the CsI counter. Typical values of the output discrimination levels, which varied to some extent from one detector to another, are shown by the broken lines in Figure 3. We see that, typically, protons with energies between 2 Mev and 160 Mev are recorded on level 5, those between 4 Mev and 40 Mev on level 4, and between 5 Mev and 16 Mev on level 3, whereas only protons entering the crystal obliquely and particles with higher charge are recorded on level 1. We see also that the energy intervals of the steps are overlapping. The response curve for the ZnS phosphor is similar with generally lower proton energies; the energy intervals are given in Table 1.

During the flight, which carried the apparatus above 90 km for approximately 200 sec, the information from the particle detectors and from a magnetometer used to find the direction of the rocket axis was telemetered to a ground station.

The results of an experiment using a nuclear emulsion carried in the nose of the same rocket will be reported in detail in a paper to be published elsewhere by Fichtel, but some of the results are presented here for comparison. It must be emphasized that these emulsion observationr are completely independent of the counter obsesvations.

Method of analysis. The section of the rocket containing the instruments was detached near the peak of the trajectory and its motion was, in general, a precession about a fixed direction in space and a spin about its axis. This motion caused the direction of maximum sensitivity of the detectors to vary over a wide range, so reconstruction of the motion using the magnetometer record allowed the generation of the magnetic zenith angle dependence of the detector rates. As the motion of the rocket was not controlled, the range of zenith angles was not complete for every flight.

During the ascent of the rocket, the Geiger counter rate was high enough on most flights at about 5 g/cm^2 residual atmospheric pressure for an intensity to be determined for those particles able to penetrate to this depth in the atmosphere. To define an intensity and an energy to which to assign it, allowance had to be made for particles reaching the Geiger counter through various thicknesses of atmosphere and rocket wall material. The observed atmospheric attenuation was used as a guide to the spectrum, and the incident particles were assumed isotropic above the atmosphere at this stage of the analysis.

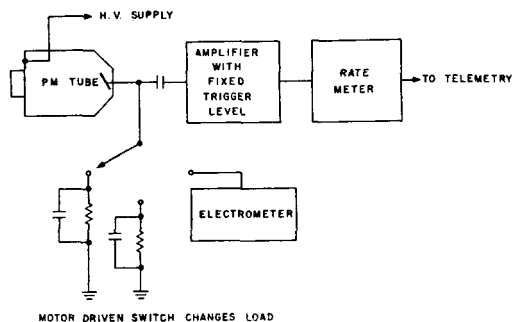For a suitable motion outside the atmosphere

Fig. 2. Block diagram of scintillation counter. The electrometer measures the total current through the phototube.
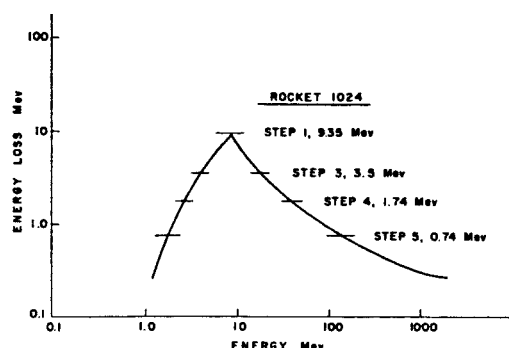
Fig. 3. Energy levels of steps superimposed upon a curve giving the energy loss of protons in the crystal.

TABLE 1

Step	Min Energy, Mev	Max Energy, Mev
2	0.2	4.7
3	0.33	2.1
4	0.45	1.6
5	0.8	1.3

The lowest discrimination levels in both scintillation counters were set at about twice the maximum energy loss for direct passage of an electron through the phosphor. Single electrons are never counted on the lowest step for the ZnS counter, and electron contamination on the lowest step of the CsI counter is at most a few per cent.

the rates observed with the window of the Geiger counter facing up and down gave two additional integral intensity values. The angular dependence of the incident particles found from the scintillation counter data was used in this analysis, but the variation of the Geiger counter rate with magnetic zenith angle is itself consistent with isotropy of the incident particles. For flights where the angle of precession of the instrument section was small, only one additional point could be found. The Geiger counter observations have been corrected for particles that are mirrored below the apparatus, and that strike the counters from below.

The fact that the energy intervals defined by the steps used in the CsI scintillation counter pulse height analysis overlap, makes it appropriate to compare the observed rates with those predicted using various trial spectra. Assuming a spectrum $N(>E) = A/E^a$, E being the proton kinetic energy, the values of the ratios of counting rates for each step to that for step 5 were calculated as a function of n. The value of n most consistent with all three observed ratios was then found; this procedure allowed calibration and statistical errors to be incorporated into the result. Allowance was again made for the effect of particles entering the crystal after passing through various thicknesses of rocket wall material, and at various angles. A comparison of calculated and observed ratios for rocket 1024 is shown in Figure 4, indicating that a consistent value of n can be found within the accuracy of the experiment. When the results were inconsistent with a simple power law spectrum, that is, if all three ratios could not be

reconciled with one value of n, a different trial spectrum was used. It can be seen, for example, for 1016, that from the calculated ratios in Figure 5, no value of n would explain nearly equal rates on steps 4 and 5. By inspecting Figure 3 we see qualitatively what form of spectrum is then indicated; there must be few particles between 16 Mev and 160 Mev, and
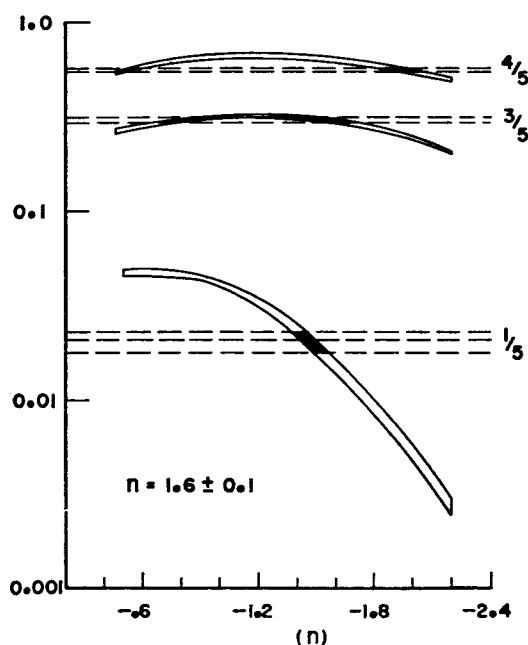

Fig. 4. Comparison of calculated and observed count rate ratios for different channels of the CsI detector of rocket 1024, assuming a power law spectrum with no cutoff above 1.8 Mev.

also few particles between 2 Mev and 5 Mev. A rather steep power law spectrum with a low-energy cutoff is therefore indicated and the values of n and the cutoff energy consistent with the three observed ratios may be found (see Fig. 6).

We thus obtain for the energy range covered by the CsI counter, 1.8 to 160 Mev, the best straight line approximation to the spectrum. When the slope of this line is known, the intensity at the lowest energy measured, either 1.8 Mev or the value of cutoff found, can be evaluated. This is illustrated by the spectra shown in Figure 9. We do not wish to imply that the spectrum has the form of a power law, but the way this spectrum intersects the points derived from the Geiger counter and emulsion measurements shows it to be a good approximation. A more complicated form of spectrum could readily be tested for consistency with our results in a similar way. Analysis of ZnS scintillation counter results was along the same lines using the ratios of rates on the steps. Here because of the steep spectrum it was not necessary to consider the effects of radiation that had not passed through the normal solid angle and
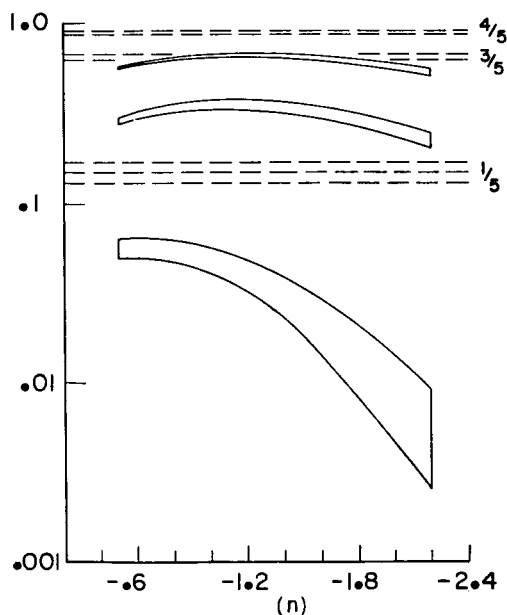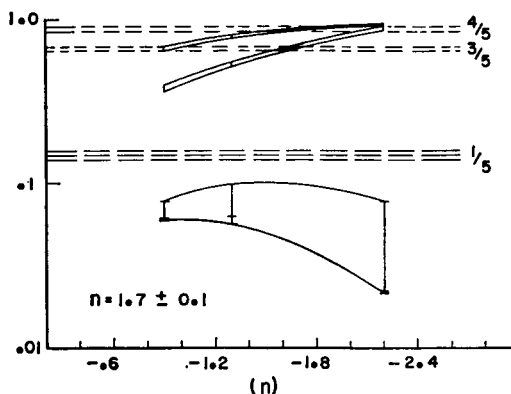
Fig. 6. Comparison of calculated and observed ratios for rocket 1016, assuming a power law spectrum with 5 Mev cutoff.

window of the counter. It was not possible to fit the observed ratios to a simple power law spectrum, however, and the ratio between the rates on the two lowest steps has been used to determine the slope shown between 0.2 and 0.35 Mev in the diagrams of the spectra. The ratios between rates on the other steps are consistent with the flat region between 0.35 and 1.4 Mev. In order to be more certain of the nature of the radiation to which the two scintillation counters were responding, absorption curves, to be discussed below, were drawn for the time when the apparatus was passing through the atmosphere.

The errors shown on the figures are computed by taking into account statistical errors for the points themselves, and also, in the case of these points derived from the ZnS scintillator, the errors in the intensity value at the higher end of the energy interval that is added to give the integral spectrum.

Results. Table 2 gives details of the rocket shots during the first November event.

Fig. 5. Comparison of calculated and observed ratios for rocket 1016, assuming a power law spectrum with no cutoff above 1.8 Mev.

TABLE 2

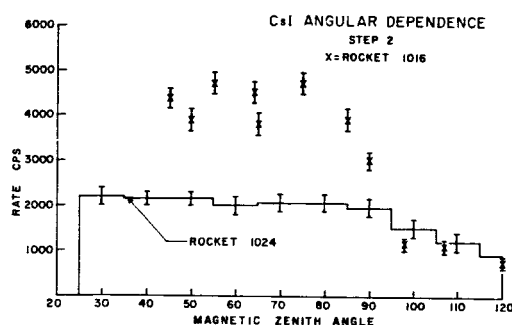| Rocket	Firing Time, UT	Time from Flare	Absorption at Ft. Church-ill, db	Emulsion Re-covery
1024	1840 Nov. 12	5 hr 27 min	12.6	yes
1015	2332 Nov. 12	10 hr 19 min	4.6	no
1016	1603 Nov. 13	26 hr 50 min	14.9	yes

Fig. 7. Angular dependence of protons detected by the CsI scintillation counter.

In order to understand these results, we must first discuss briefly the nature of the very complicated November 12 solar proton event [*Oertner, Egeland, and Hultquist*, 1961; *Steljes, Carmichael, and McCracken*, 1961; *Roederer, Manzano, Santochi, Nerurkar, Troncoso, Palmeira, and Schwachheim*, 1961]. The solar region 5925 was close to the central meridian of the sun, and it was in this region that the flare observed for the first time at 1323 UT on the 12th occurred. On the previous day no flare of this importance was observed, but an SID of importance 3+ lasting for 4½ hours started at 0316 UT. An sc magnetic storm, which is attributed to the flare of November 11, started at 1348 UT on November 12. Thus the magnetic storm-producing particles from this flare had a transit time of 34 hours to the earth. Riometer observations at Fort Churchill show that the absorption started to increase there at 1345 UT, indicating the arrival of solar protons. The cosmic ray increase observed by neutron monitors started at 1345 UT and had a relatively slow rise. These facts are illustrated in Figure 10.

After the initial rise in the neutron monitor rate, it appeared to remain approximately constant for a period of 180 minutes, between 1600 UT and 1900 UT. Toward the end of this time rocket 1024 was fired. The neutron monitor then increased at a much more rapid rate, reached a peak about 2000 UT, and then decreased again. Rocket 1015 was fired into the decrease, and 1016 at a later time when the monitor rate was almost normal and a smooth decrease had set in. These three rockets comprise the observations we have of the November 12 event.

A tentative interpretation of this event has been proposed by *Steljes, Carmichael, and McCracken* [1961] and will be summarized here because we shall later wish to see how our data fit into this picture.

A Forbush decrease began at 1930 UT on November 12 and, starting at 1900 UT, geomagnetic fluctuations occurred. This is interpreted by assuming that a gas cloud with frozen-in magnetic fields enveloped the earth at a time between 1900 and 1930 UT. Prior to this envelopment, the earth was therefore separated by a magnetic barrier from a field region connecting to the surface of the sun. To reach the earth at this time solar protons had to leak across the barrier, presumably by diffusion. This was the situation at the time of firing of rocket 1024, and the rate of rise of the high-energy particles detected by the neutron monitor, the absence of impact zones, etc., support this diffusion idea. The comparatively flat neutron monitor rate curve at the time of firing of 1024 is evidence that a stable situation existed for the particles detected by the neutron monitor and probably also existed for the solar protons. Within the magnetic region the intensity of galactic cosmic rays was reduced, but that of solar particles increased. Rockets 1015 and 1016 sample, according to this interpretation, the intensity of particles inside the trapping region at two times after the time of maximum flux at high energies. It must be pointed out that the threshold rigidities must undergo large changes during such an event. At Fort Churchill, the threshold energy is in any case less than 10 Mev, so we shall have to consider magnetic field changes in connection with measurements at less than 10 Mev energy.
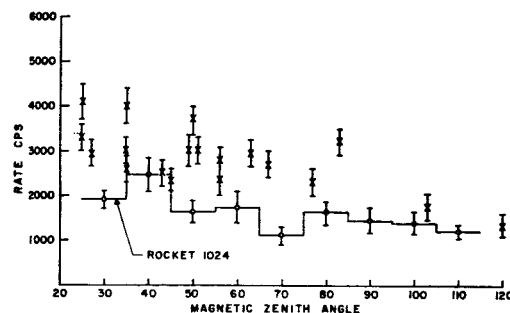

Fig. 8. Angular dependence of protons detected by the ZnS scintillation counter.
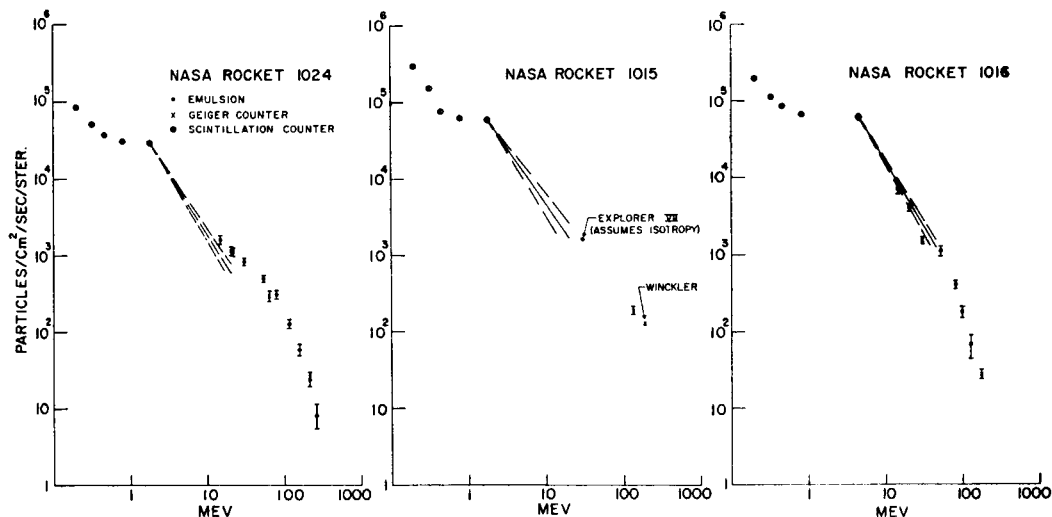
Fig. 9. Spectra of protons from the three rocket flights.

In Figure 7 we show the magnetic zenith angular distribution found for flights 1024 and 1016 for the CsI scintillation counter (step 5 sensitive from 1.8 Mev to 160 Mev). This shows the assumption of isotropy to be well fulfilled in the upper hemisphere, for angles between 25° and about 90°. The fall-off in the lower hemisphere is not sharp, owing to the ±15° opening angle of the detector. The flux at angles greater than about 110° is due to particles scattering below the apparatus, and also those being mirrored by the magnetic field and returning from below. The angular distribution for step 2 of the ZnS scintillator, shown in Figure 8, shows more variation. Isotropy just above the atmosphere does not of course mean isotropy in space away from the earth's magnetic field.

The integral proton energy spectra found by analysis of the first three flight records are shown in Figure 9. The shape of the spectra are generally similar, with a gradual lessening of slope in the region down to a few Mev, and an increase in flux at even lower energies.

In the diagram of the spectra, the point marked 'Explorer VII' indicates the flux values given by Lin [1961], divided by 4π, obtained from the Explorer VII results. The satellite was at an altitude of 877 km, 44° latitude, and 300° longitude at the time of firing of rocket 1015; the magnetic field line passing through this point crosses the equator at about three earth radii.

The point marked 'Winckler' on Figure 9 is derived from the observations made by Winckler's group at Fort Churchill during the event.

Balloon observations have previously indicated spectra with exponents in the range 4–5, above about 100 Mev [Winckler, 1960]. It is now clear that extrapolation of the balloon spectra to low energies is not a satisfactory procedure. The intensity found by balloon measurements at the time of rocket 1015 do agree, however, with our measurements at the corresponding energy.

As we stated earlier, when discussing the method of analysis used for the CsI scintillation counter results, these observations for rocket 1016 require the assumption that no particles are present between 1.8 Mev and 4.5 Mev. This indicates the existence of a cutoff, which also appears in the results of 1024 and 1015 as a short flat portion in the integral spectrum between about 0.35 Mev and 1.8 Mev. Rocket 1024 was fired 1 hour and 31 minutes after the start of the main phase of a geomagnetic storm, which was still going on [Steljes, Carmichael, and McCracken, 1961] when 1015 was fired. It is thus possible that these cutoffs represent the magnetic thresholds at Fort Churchill at the time of firing of the rockets. Magnetometer X-component records for Kiruna [Oertner, Egeland, and Hultquist, 1961] show a considerably

reduced field at the times of firing of 1024 and 1015, but attempts to correlate the value of cutoff with readings from Canadian magnetometers [*Niblett*, 1961] have not been successful. The Quenby and Webber threshold calculated for Fort Churchill is 5.8 Mev, but large uncertainties are expected in this region. An external ring current, such as is thought to exist during a magnetic storm, can reduce the thresholds to zero at these latitudes (Webber, to be published).

We must now consider the rising portion of the spectrum below 0.4 Mev. Auroral absorption was not shown on the Churchill riometer at the time of any of the shots, but at the firing times of 1024 and 1016 the instrument was almost off scale and not very sensitive. Proton intensities of similar order of magnitude and spectrum have been observed in and near auroras by *Davis, Berg, and Meredith* [1960]; *McIlwain* [1960]; and recently by *McDiarmid* [1962].

In order to be certain that the ZnS counter responds to protons in the apparent energy range, we examined the absorption curves for the period when the rocket was passing through the atmosphere. These show that the ZnS counter rate began to rise at about the correct time, and that the CsI and ZnS counter rates bear the correct relationship to one another until late in the ascent when the low-energy particles could get into the ZnS counter.

We define ΔJ as the difference between the intensity recorded on step 2 of the ZnS counter and step 5 of the CsI counter; that is, the additional intensity at low energies.

In Figure 10 we show the Deep River neutron monitor rate [*Steljes, Carmichael, and McCracken*, 1961], the Fort Churchill riometer absorption, the intensity at three energies, and ΔJ plotted against time.

If we assume a day to night ratio of 3 : 1 [*Reid*, 1961], the riometer absorption and the intensity of particles with energy greater than 10 Mev (extrapolated from 22 Mev) correlate well. Comparison of the intensities at the three energies shows the rapid steepening of the spectrum toward high energies that has been previously noted by many observers. The figure also shows that the riometer absorption is predominantly produced by particles in the range between 10 and 100 Mev.

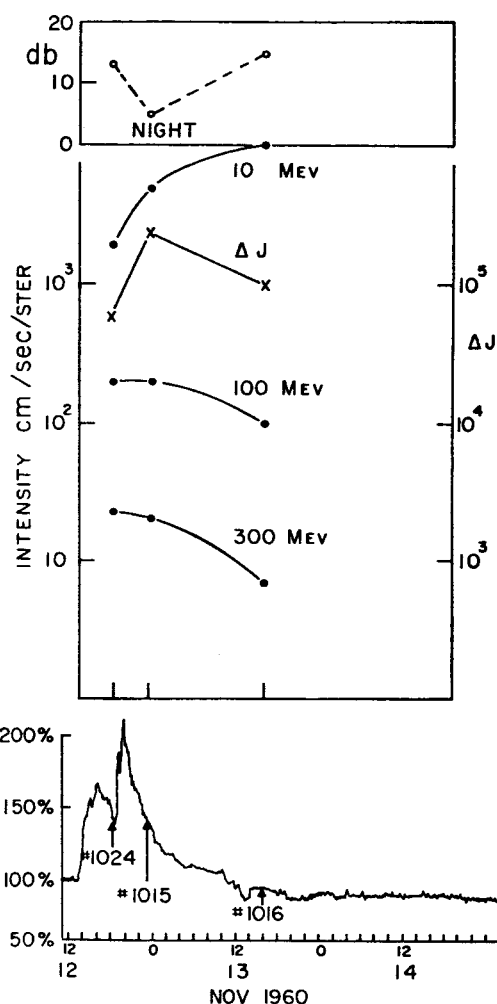Table 3 shows that ΔJ underwent a large

Fig. 10. The variation of intensity 30 Mc/s riometer absorption at Fort Churchill and neutron monitor counting rate during November 12, 13, and 14, 1960. Also shown are the intensities above 10 Mev, 100 Mev, and 300 Mev and ΔJ as defined in the text.

increase between the times of rockets 1024 and 1015, during the time when the earth was supposed to be entering the trapping region, and a considerable decrease again by the time of firing of 1016. Thus the entry of the earth into the magnetic cloud produced a much larger increase in the intensity of these particles than in the higher-energy particles.

This experiment cannot clearly determine whether the additional very low energy particles

TABLE 3

Rocket	ΔJ	J_{10}*	$\Delta J/J_{10}$	Time from Flare
Nov. 12, 1960				
1024	6×10^4	2×10^3	30	5 hr 27 min
1015	24×10^4	5×10^3	48	10 hr 19 min
1016	14×10^4	10^4	14	26 hr 50 min
Sep. 3. 1960	≈ 700	≈ 46	≈ 14	17 hr

* J_{10} = intensity of particles with energy greater than 10 Mev.

represent a simple extension of the spectrum of particles from the sun, in which case the cutoffs observed do not correspond to threshold rigidities, or whether they are a separate phenomenon. If they are, this suggests that we are observing the high energy tail of the distribution of protons responsible for the magnetic disturbances, and that these are not excluded by the threshold. The rocket observations cited [*Davis, Berg, and Meredith,* 1960; *McIlwain,* 1960; *McDiarmid,* 1962] strongly suggest that these protons are present in some quantity for a high proportion of the time at Fort Churchill.

Magnetic field lines cutting the earth at Fort Churchill cross the equator at a distance of ~ 8 earth radii in quiet conditions. Moving under the influence of the disordered magnetic field of the plasma cloud, these low-energy particles may be able to transfer to the field lines. The flat portion of the spectrum observed here would then represent the change-over between motion in Stoermer orbits and injection directly into the field by plasma, and leaves open the question of the spectrum below 10 Mev outside the field. Supporting the idea that the additional low-energy particles are associated with the magnetic storm is the fact that, at 0.2 Mev, the rectilinear travel time from the sun is 7 hours, so that such particles emitted by the flare could not have been observed by rocket 1024. By the time of rocket 1015, when a very large intensity of such particles was observed, the particle path length would have to have exceeded the direct path length by less than 50 per cent. This is an interesting contrast to the behavior of the intensity at 10 Mev, which was still rising at

26 hours after the flare, more than twenty times greater than the time for rectilinear passage from the sun.

Again, due to the complicated nature of the event, we cannot exclude the possibility that the lowest energy particles were produced by the flare, probably of importance 3$^+$ and accompanied by an SID of duration 4½ hours and type IV radio emission, which occurred at 0316 UT on November 11. This flare did not produce a neutron monitor increase or an effect on the riometer.

The rocket NASA 1020, shot at 1730 UT on September 3, 1960, recorded particles in this low-energy range. There was a magnetic cloud close to the earth at the time, but the sc and Forbush decrease did not occur until 0230 UT on the 4th [*Winckler,* 1961]. This suggests a different interpretation of the spectral slope to be discussed below.

In the passage of a beam carrying trapped high-energy particles from the sun to the earth, an adiabatic deceleration must occur. *Sklovsky* [1960], applying this idea to an expanding supernova, obtains an expression for the energy change ΔE per collision, for a particle of velocity v, colliding with magnetic scattering centers moving with velocity u in an envelope expanding with velocity V

$$\Delta E = Mc^2 \left[\frac{u^2}{c^2} - \frac{avl\,V}{c^2 r} \right]$$

In this result l is the distance apart of the scattering centers, a is a constant of order unity, and r the radius of the region of expansion, which is assumed spherical.

It can be seen that for particles of low velocity ($v < u, V$) an acceleration is predicted. This is because these particles are mainly in contact with the randomly moving scattering centers, not the advancing barrier. This acceleration may not operate below a certain injection energy, so that particles below this energy in the original spectrum will not be removed. Also there is still the fact that our observations with rocket 1024 show such particles before they could have arrived from the sun.

It would be interesting to compute whether the change in slope of the spectra at energies of the order of 50 Mev, and the flat portion at about 4 Mev, could be accounted for by such a

mechanism and independently of a magnetic threshold.

Conclusions. 1. The spectrum of protons at all times has a generally similar form and cannot be adequately represented at low energies near the earth by an extrapolation of the power law appropriate at balloon altitudes. The spectra observed here are not necessarily appropriate at large distances from the earth.

2. The particles are isotropic in the upper hemisphere just above the atmosphere.

3. The observed low-energy particles are either the high-energy part of the magnetic storm distribution or, less likely, are the results of the modification of the initial spectrum by the expansion of the solar plasma cloud in which the trapping occurs, or a combination of both. The most reasonable interpretation is that the observed cutoffs represent the magnetic thresholds at the time, that the low-energy particles enter the field by another mechanism, and that the shape of the spectrum above the cutoff is influenced by the expansion of the trapping region.

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